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ADVANCED DETECTOR DEVELOPMENT, LABORATORY SIMULATIONS, DIAGNOSTIC DEVELOPMENT, AND DATA ANALYSIS ON WAKE PHYSICS

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13. ABSTRACT *(Maximum 200 words)*
We have performed a number of experiments and have developed a theoretical analysis of the current scaling issues of a negatively biased probe in a plasma wake. The end product of the laboratory research performed in the large vacuum chamber JUMBO at Phillips Laboratory can be found in the associated publication (Enloe et. al, 1993). Theoretical assumptions have been analyzed qualitatively and quantitatively by the use of the POLAR computer code. For a plasma with a constant beam energy, the analysis shows that the I-V collection characteristics are unaffected by Mach number variations for Mach numbers above the value of two. For the same case, the current was found to scale with the 3/7 power of the density.

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ILLUSTRATIONS

1. INTRODUCTION

The investigation of both theoretical effects and computer simulation models of the collection of ion current by a Langmuir probe in the plasma wake of a shadowing body is the focus of this report. For the first year, Steven Meassick of Northeastern University and C. Lon Enloe of Phillips Laboratory performed a number of experiments and laboratory simulations to gain a better understanding of the physical issues involved and to assure that the WSF/CHAWS hardware would perform as expected. The experimental work was performed in the large vacuum chamber JUMBO at Phillips Laboratory. The end product of the research can be found in the associated publication [Enloe *et. al.*, 1993]. The study determined that the plasma wake would be mostly ion free. The physical development of the Micro Channel Plate Detectors (MCP's) also lead to modifications of the Retarding Potential Analyzers (RPA's). Many people (Northeastern University, Wentworth Institute of Technology, PL/SX, ATC, AmpTek, PL/GP) were also involved in the refinement of the MCP and RPA structures. The detectors were integrated in their respective probes and tested in the vacuum chamber MUMBO at PL using the flight power and control systems. The entire probe and control assemblies were tested in ambient plasma conditions to ensure proper operation of the entire system, as the previous tests used only part of the system.

The second year incorporated John M. Talbot of Northeastern University, under the advisory of Dr. David Cooke at PL, to model the current collection characteristics of the Langmuir probe in a plasma wake using the three-dimensional POLAR simulation computer code. While POLAR was developed to simulate the problem of current collection on space craft surfaces, it was not intended to solve the problem of current collection on the biased object in the wake of a second larger object. The code experiences convergence problems where the calculated ion densities in the wake region, and therefore the current collected on the biased object, shows large oscillations about a linear region of convergence. In order to solve this problem, we modified the POLAR code and introduced a "mixing term" in which a fraction of the ion density from the previous iteration of the code is averaged with the current ion density. This averaging over iterations smoothes the oscillations and allowed the code to converge to a solution. This revision of the POLAR code has revealed several characteristics of the predicted and previously measured wake phenomena. For high ion densities in the wake region, the sheath about the Langmuir probe will retain a small surface area until the corresponding densities within the sheath have been reduced by ion collection. For low initial densities in the wake region, a large initial sheath region forms until ions from the surrounding area compensate for ions collected by the Langmuir probe. The POLAR code was further modified to attempt a modeling of the plasma source point of the chamber experiment. The goal was to modify the initial trajectories into the sheath as though originating from a source point instead of a collimated plasma stream. The routine was implemented by applying a rotational matrix operator to the Mach vector associated with each tracking particle along the plasma sheath. The modifications proved to estimate only a 10% change in the ion current collected by the Langmuir probe. A secondary advantage of the implementation of this routine lead to modifications of the POLAR code to furtherly "double-check" ion trajectories during the tracking process, providing more accurate results for future computations.

The results of the laboratory experiments and the POLAR simulations have been used in flight predictions [Cooke *et. al.*, 1994] of the WSF-CHAWS STS-60 spaceflight mission. It has been found that the collection of ion-current in a plasma wake is a space-charge-limited process with a strong dependence upon angular-momentum mechanisms. Previous attempts [Enloe *et. al.*, 1993; Cooke *et. al.*, 1994] have been made to model effects of scaling plasma parameters and pose theoretical models to asses the variations of current collection with the variations of plasma parameters. Although expected by orbit-limited models of ion collection in the plasma wake, the magnitude of the collected current is not a linear function of plasma temperature (T), plasma density (N), nor ion Mach number (M).

2. THEORETICAL MODELS

Given that the angular momentum of the particles is a dominant characteristic of particle collection in the wake [Enloe *et. al.*, 1993], we must speculate on the impact of the scaling of particular plasma parameters for both orbit-limited and space-charge-limited analytical approaches. For the scope of our study, we look at the first order impact of the most dominant plasma parameters: plasma density, temperature, Mach number, and atomic mass number. In any plasma environment, we know that the ion thermal velocity is proportional to the square root of the plasma temperature to mass (AMU) ratio; more conveniently written:

$$v_{th} \quad = \quad (kT / m_i)^{1/2} \quad \propto \quad (T / AMU)^{1/2}. \qquad (2.1)$$

For a moving object in a stationary plasma or a stationary object in streaming plasma, we know that the relative plasma stream velocity (v_0), ram current density (J_{ram}), and the plasma beam energy (E_0) are related as:

$$v_0 = M\,v_{th} \propto M\,(T/AMU)^{1/2} \tag{2.2}$$
$$J_{ram} = e\,N\,M\,v_{th} \propto N\,M\,(T/AMU)^{1/2} \tag{2.3}$$
$$E_0 = (1/2)\,m_i\,v_0^2 \propto M^2\,T \tag{2.4}$$

where M is the mach number of the streaming plasma relative to the object immersed in the plasma. From orbit-limited theory, we would expect that an increase in the ram current density by a factor of two would be followed by an increase in current collection by a factor of two. From space-charge-limited theory for a body, such as the WSF-CHAWS experiment, where the dimensionless characteristic radius ($r=R/\lambda_D$) is much greater than unity, the current collection of a probe in a plasma is limited by the Debye shielding of the plasma sheath set up by the probe potential [Langmuir and Blodgett, 1924]. Otherwise, we can assume that the current collection in the wake of the WSF-CHAWS experiment is orbited limited when the dimensionless characteristic radius is less than unity. Such a case can occur when the density is at a critical minimum, thus making the influence of the Debye length more appreciable to the characteristic radius (R) of the experiment. In the case of the WSF-CHAWS experiment, a ram density on the order of 10^4 becomes highly unlikely for a body in LEO . Therefore, we can assume that a simple scaling of the ram flux density and the associated collected wake current, as in accordance with the previous orbit-limited assumption, once again is inaccurate.

2.1. Mach Number and Plasma Temperature Variations

Reverting to a more basic approach, we must first concentrate on known relations. In congruence with the WSF-CHAWS spaceflight operation, we know that the orbital speed of the shuttle and WSF is nearly constant. This constant velocity, for any given species of plasma, denotes that the streaming velocity (beam energy) of the plasma also will be a constant, relating T and M appropriately by Eqn. 2.4:

$$M^2 \propto \frac{1}{T} \tag{2.5}$$

To model the physical effects of the variations of these parameters, we look at the ram flux from the origin of the plasma wake disturbance at the edge of the WSF-CHAWS shadowing body. Since the WSF-CHAWS experiment is traveling in the -Z direction at a constant velocity v_{zo} and a transverse ion expansion into the wake with a mean velocity of v_{xo}, we have the corresponding distribution function:

$$f = N\left(\pi v_{th}^2\right)^{-3/2} e^{-\left[v_y^2+\left(v_x-v_{xo}\right)^2+\left(v_z-v_{zo}\right)^2\right]/v_{th}^2} \tag{2.6}$$

Integrating this function with respect to each velocity component

$$F = N\left(\pi v_{th}^2\right)^{-3/2}\left[\left(\pi v_{th}^2\right)^{1/2}\left[\int_{-\infty}^{+\infty} e^{-\left(v_x - v_{x0}\right)^2/v_{th}^2} dv_x\right]\left[\int_0^{-\infty} e^{-\left(v_z - v_{z0}\right)^2/v_{th}^2} dv_z\right]\right], \quad (2.7)$$

yields

$$F = N\frac{v_{th}}{2\sqrt{\pi}}\left[\frac{v_{zo}\sqrt{\pi}}{v_{th}}\left(1+\mathrm{erf}\left(\frac{v_{zo}}{v_{th}}\right)\right)+e^{-v_{z0}^2/v_{th}^2}\right], \quad (2.8)$$

which agrees with Parker [1980]. Analysis of this result provides important information about the effect of the plasma temperature (Mach number) on the ram current density. For Mach numbers above the value of two in Eqn. 2.8, the error function saturates to unity and the negative exponential saturates to null, indicating that the flux distribution is unaffected by Mach numbers above the value of two. In comparison to oxygen ions in LEO, the WSF-CHAWS experiment operates in a Mach number range above the value of seven. Therefore, the collection of current due to oxygen ions on a probe in the WSF-CHAWS wake is invariant to perturbations in the plasma temperature. For hydrogen ions in the same environment, the WSF-CHAWS experiment operates in a Mach number range near the value of two, indicating that the ram density characteristics may be dependent upon the plasma temperature.

2.2. Plasma Density Variations

Although variations in the plasma temperature (Mach number) have little effect on the I-V characteristics of the Langmuir probe in the WSF-CHAWS wake, variations of the ambient ion density of a LEO environment exist. As Eqn. 2.8 shows, the flux density is directly proportional to the density of the plasma. As stated before by the orbit-limited theory, we can assume that the current collection in the wake will be proportional to this density, but first we must look at the effect of the density on the space-charge-limited collection of a Langmuir probe according to Langmuir and Blodgett [1924]. From the well-known Child-Langmuir law of space-charge-limited current between charged concentric spheres, we have

$$J = \frac{4}{9}\sqrt{\frac{2e}{M}}\frac{\varepsilon_0 |V|^{3/2}}{D^2}, \quad (2.9)$$

where ε_0 is the permittivity of free space, V is the potential difference between the spheres, and D is function of the radii of the spheres. Using the three dimensional flux density to a surface (let $J_0 = eN[kT/2\pi M]^{1/2}$), Debye length, and dimensionless potential, Eqn. 2.9 can be written

$$D = \left[\left(\frac{4}{9}\right)\sqrt{\frac{2e}{M}}\frac{\varepsilon_o\left(\frac{\Phi kT}{e}\right)^{3/2}}{J_o} \right]^{1/2} = (1.2)\lambda_D\Phi^{3/4}. \tag{2.10}$$

From the Parker [1980] tabulation of Table II of Langmuir and Blodgett [1924],

$$\frac{R_s}{R_o} = \left(\frac{D}{R_o}\right)^{0.5666} \approx \left(\frac{D}{R_o}\right)^{4/7}, \tag{2.11}$$

where R_o is the characteristic radius of the Langmuir probe and R_s is the sheath radius. Incorporating Eqn. 2.10 into Eqn. 2.11, yields

$$R_s = R_o\left(\frac{\lambda_D}{R_o}\right)^{4/7}\Phi^{3/7}. \tag{2.12}$$

Using 2 12 as the radius of the spherical sheath,

$$I = 4\pi J_o R_s^{\,2} = 4\pi J_o\left[R_o\left(\frac{\lambda_D}{R_o}\right)^{4/7}\Phi^{3/7}\right]^2. \tag{2.13}$$

From the definition of the ion Debye length and the proportion of Eqn. 2.1, the current to the Langmuir probe is proportionally related

$$I = 4\pi J_o R_s^{\,2} \propto NT^{1/2}\left[\left(\sqrt{\frac{T}{N}}\right)^{4/7}\left(\frac{1}{T}\right)^{3/7}\right]^2 = N^{3/7}T^{3/14}. \tag{2.4.14}$$

Therefore, we see that for a non-flowing plasma, the space-charge-limited current varies with the $^3/_7$ ths power of the variation of the plasma density. The $^3/_{14}$ ths power variation associated with the plasma temperature is considered ineffective via the derivation of Eqn. 2.8. To apply a similar reasoning to the plasma stream that evolves about the edges of the shadowing body proves to be rather difficult. We cannot assume a spherical sheath as in Eqn. 2.13, nor is the plasma density in the wake uniformly distributed about a spherical probe. What is important is the power relation of the density to the Langmuir probe current. On the other hand, if we assume that the collection potential of a Langmuir probe in a plasma wake is sufficiently high enough ($V \gg kT/e$) above some collection threshold, we can (for the moment) disregard the angular momentum properties of ion trajectories in the sheath and use the Langmuir-Blodgett relation for the current scaling with density. Such a situation is physically unrealizable because the sheath edge is not well defined and the initial velocities of the ion trajectories into the sheath are highly dependent upon the angular momentum of the ion particle. From this, we can conclude that the current collection mechanism in the plasma wake is neither orbit-limited or space-charge-limited. Rather, it is in a quasi-space-charge-orbit-limited regime where the current scaling via the density can be described mostly by the relation of Eqn. 2.14 in the space charge sense, but the particles also exhibit some behavior relevant to angular momentum concepts.

3. EXPERIMENTAL RESULTS

We have used the POLAR [Lilley *et. al.*, 1985] computer simulation to model the chamber experimentation [Enloe *et. al.*, 1993] and the WSF-CHAWS STS-60 mission [Cooke *et. al.*, 1993] with good results. The POLAR code was able to model the chamber experiment as shown in Figure 1. The *in situ* results [Enloe *et. al.*, 1993] and POLAR simulations are shown respectively in Figures 2 and 3. The identification of the "sweet spot" of orbiting ions and similarities in the magnitude of current collection provided a reasonable validation. A similar geometry, shown in Figure 4, was used to model the parametric variations more closely by removing the effects of the ion circulation about a Langmuir probe with quasi-radial symmetry. The small effects of Mach number and plasma temperature variations are shown in Figure 5. The effects of plasma density variations and the Langmuir-Blodgett scaling assumption is shown in Figure 6. Similar relations of the plasma density variations are also present in the Cooke *et. al.* [1994] data.

4. CONCLUSIONS

From the theoretical assumptions and predictions of the POLAR simulation models, we see that variations in the Mach numbers and plasma temperature have little effect on the ion current characteristics of collection when the Mach number is greater than two. It was found that the collection of ions to a Langmuir probe in the plasma wake of a shadowing body is a space charge limited process that is heavily dependent on the angular momentum of the particles. The collected ion current is expected to scale with variations in the plasma density to the $^3/_7$ ths power.

5. PUBLICATIONS

During the time period covered by this report, a number of scientific papers were presented at professional meetings or submitted for publication.

Meassick S., C. Chan, C. Enloe, D. Cooke, "Studies of Temporal Evolution of the Current-voltage Characteristic of a Probe Immersed in the wake of a Flowing Plasma: Experiment and Theory," 1992 IEEE Conference on Plasma Science, Tampa, FL, June 6-8, 1992.

Biasca, R., D. Cooke, C. Enloe, C. Chan, S. Meassick, J. Talbot, and M. Tautz, "Current Collection in a Spacecraft Wake: A Comparison of Laboratory Experiments and Computer Simulations," 1992 American Geophysical Union, Fall Meeting.

Enloe, C. L. D. L. Cooke, S. Meassick, C. Chan, and M. F. Tautz, "Ion Collection in a Spacecraft Wake: Laboratory Simulations," J. Geophys. Res., v98 No. A8, p. 13,635, August 1, 1993.

Cooke, D., J. Talbot, G. Shaw, "Preflight POLAR Code Predictions for the CHAWS Space Flight Experiment," PL-TR-94-2056, January, 1994, ADA280951.

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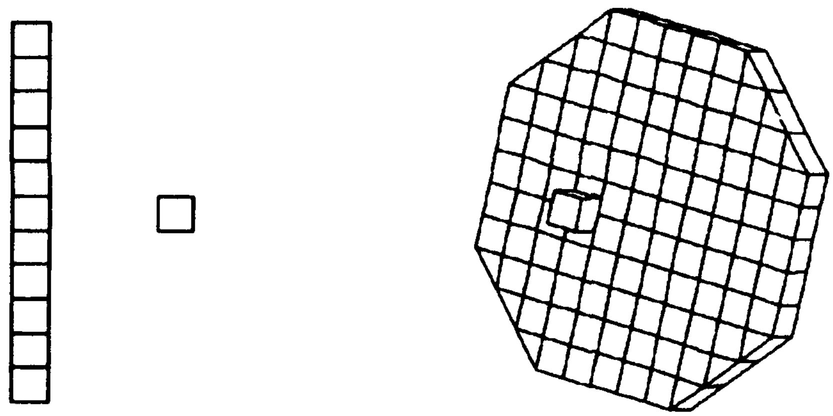
Langmuir, I., K. Blodgett, "Currents Limited By Space Charge between Concentric Spheres," Phys. Rev., v24, p.49, July, 1924.

Lilley, J., Jr., D. Cooke, G. Jongeward, and I. Katz, "POLAR User's Manual", AFGL-TR-85-0246, 1985, ADA173758.

Parker, L. W., "Plasmasheath-Photosheath Theory for Large High-Voltage Space Structures," in *Space Systems and their Interactions with Earth's Space Environment*, Prog. in Astro. and Aero., H. B. Garret and C. P. Pike, v71, p. 477, 1980.



a.) b.)

Figure 1. POLAR Chamber Simulation Shadowing Body and Langmuir Probe Configurations: a.) side-view (x-z) of POLAR object, b.) three dimensional view.

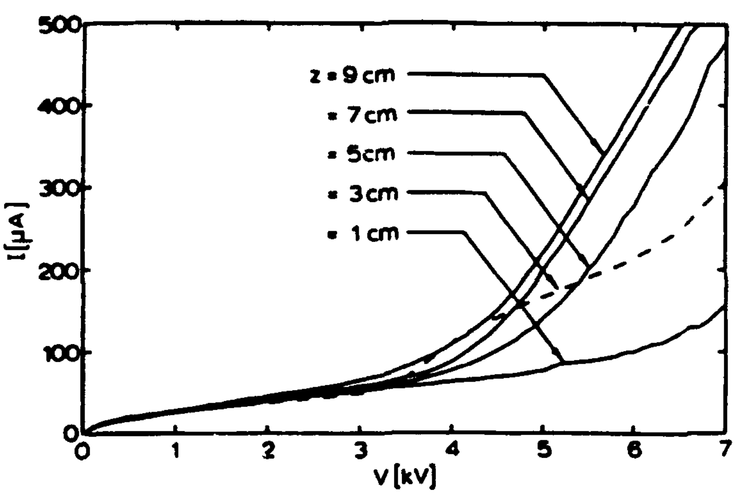


Figure 2. Current collected as a function of negative potential on the Langmuir probe for varying axial positions. The change in the shape of the I-V curve for z = 3 cm is due to the effect of the ions orbiting the sphere [Enloe *et. al.*, 1993].

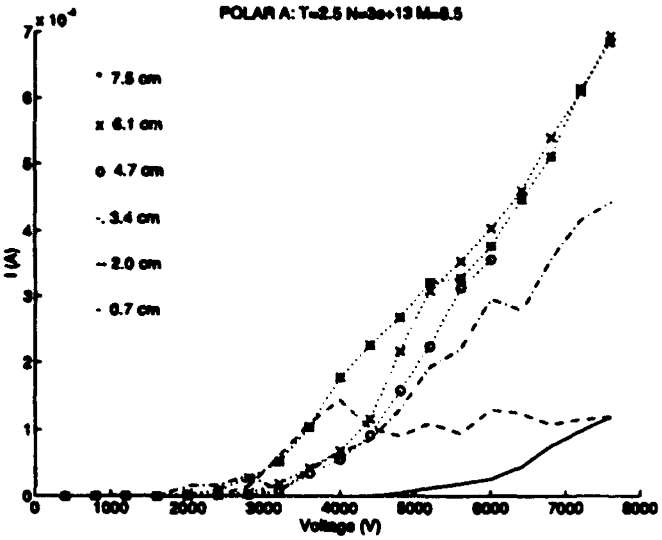
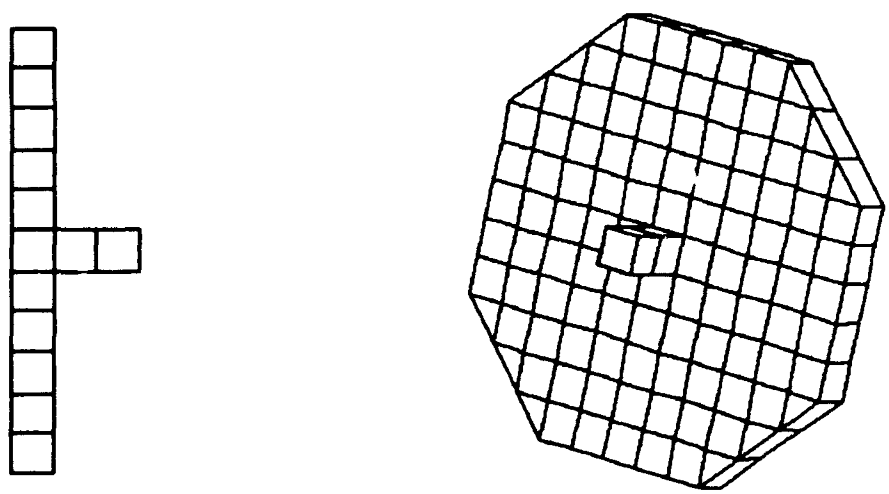


Figure 3. Current collected as a function of negative potential on the Langmuir probe for varying axial positions from the POLAR simulation.



a.) b.)

Figure 4. POLAR simulation shadowing body and Langmuir probe configurations used to limit effects of ion circulation: a.) side-view (x-z) of POLAR object, b.) three dimensional view.

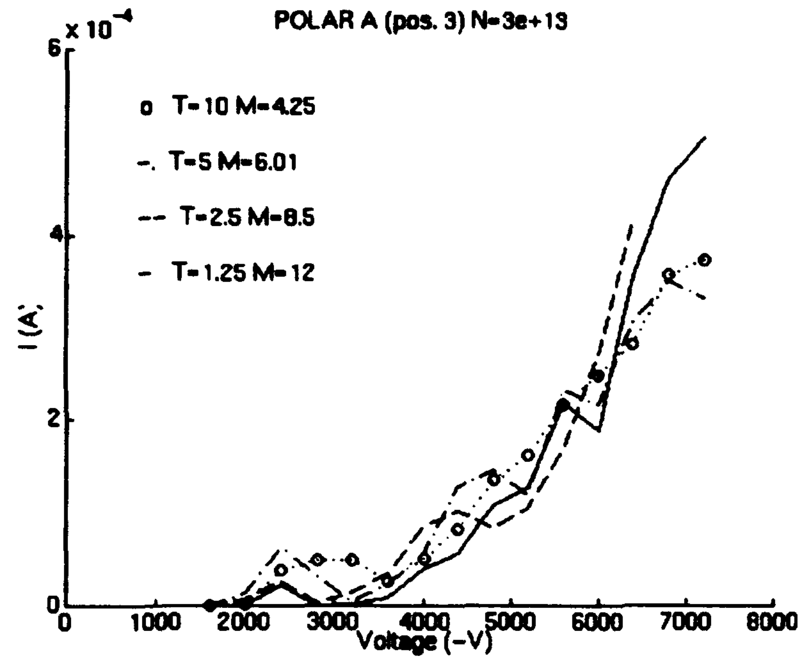
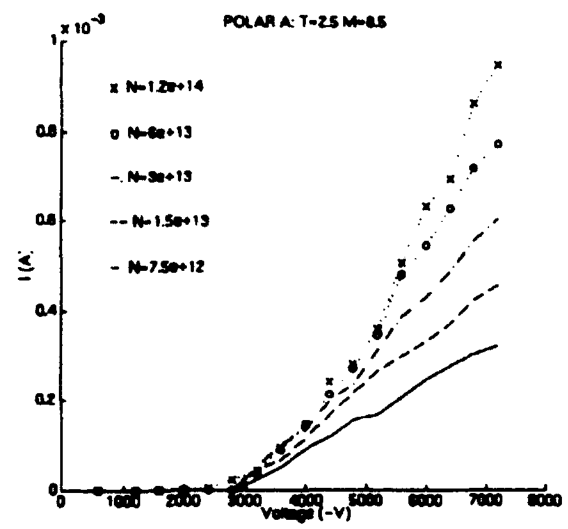
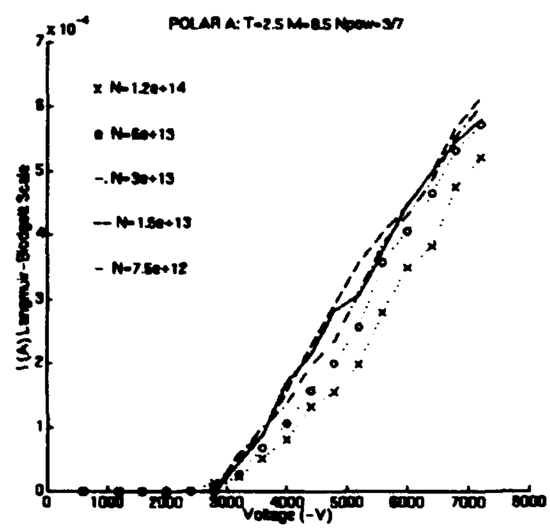


Figure 5. I-V collection characteristics as a function of plasma temperature and related Mach number.



a.) No density scaling.



b.) Langmuir-Blodgett density scaling.

Figure 6. I-V collection characteristics as a function of density. The single element Langmuir probe was replaced by an elongated probe extending from the shadowing body to prevent trajectory orbits.